Initial Performance from the NOνA Surface Prototype Detector

M. Muether[a,1]

[a] *Fermi National Accelerator Lab, Neutrino Department, P.O. Box 500 MS-220, Batavia, IL 60510 USA*

Abstract

NOνA, the NuMI Off-Axis ν_e Appearance experiment, will study $\nu_\mu \rightarrow \nu_e$ oscillations characterized by the mixing angle Θ_{13}. Provided Θ_{13} is large enough, NOνA may ultimately determine the ordering of the neutrino masses and measure CP violation in neutrino oscillations. A complementary pair of detectors will be constructed $\sim$14 mrad off beam axis to optimize the energy profile of the neutrinos. This system consists of a surface based 14 kTon liquid scintillatior tracking volume located 810 km from the main injector source (NuMI) in Ash River, Minnesota and a smaller underground 222 Ton near detector at the Fermilab. The first neutrino signals at the Ash River Site are expected prior to the 2012 accelerator shutdown. In the meantime, a near detector surface prototype has been completed and neutrinos from two Fermilab sources have been observed using the same highly segmented PVC and liquid scintillator detector system that will be deployed in the full scale experiment. Design and initial performance characteristics of this prototype system are being fed back into the design for the full NOνA program.

Keywords:

1. Introduction

NOνA, the NuMI Off-Axis ν_e Appearance experiment, is a next generation neutrino oscillation experiment which will study $\nu_\mu \rightarrow \nu_e$ oscillations at a baseline of 810 km (L/E of 400 km/GeV). Provided Θ_{13} is as large as early indications from the T2K experiment [1], NOνA will have the reach to determine the ordering of the neutrino masses and constrain the CP violating phase in neutrino oscillations. Additionally, NOνA will study the differences in the oscillation parameters between neutrinos and antineutrinos, as well as make a precision measurement of Θ_{23} by observing muon neutrino disappearance.

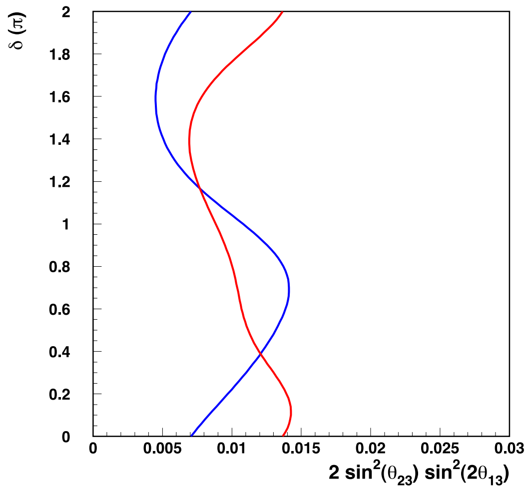
Achieving these goals requires a detector with 14 kTons of material capable of suppressing ν_μ charge current (CC) and neutral current (NC) backgrounds (Fig. 2(b)) at the 99% level. Additionally, good ν_e detector efficiencies and energy resolution less than 8% of the expected signal width for ν_e CC event are required. Meeting these specification would provided the sensitivities to Θ_{13}, the mass ordering, and Θ_{23} as shown in Figures 1(a), 1(b) and 1(c) [2].

2. Experimental Design

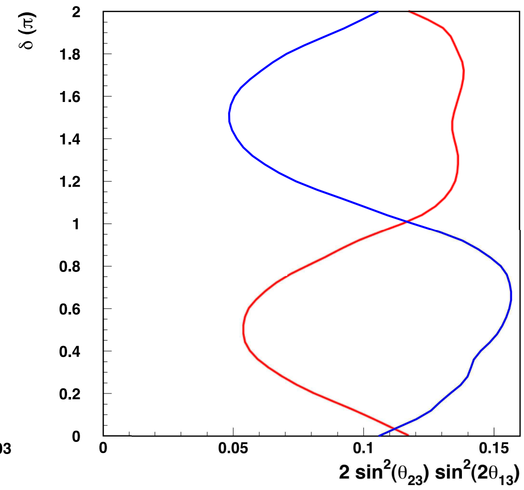
2.1. Beam

To achieve the goal of the NOνA project, two detectors will be placed 14 mrad off-axis to the primary direction of the NuMI (Neutrinos from the Main Injector) source. As shown in Figure 2(a), the ν_μ flux near the first $\nu_\mu \rightarrow \nu_e$ oscillation maximum at around 2 GeV is optimized at this angle [2]. The off-axis beam also reduces high energy neutral current background events (Fig. 2(b)). To accommodate the needs of the experiment, the NuMI beam power will be upgraded to 700 kW during the shutdown of the accelerator from March to December 2012.

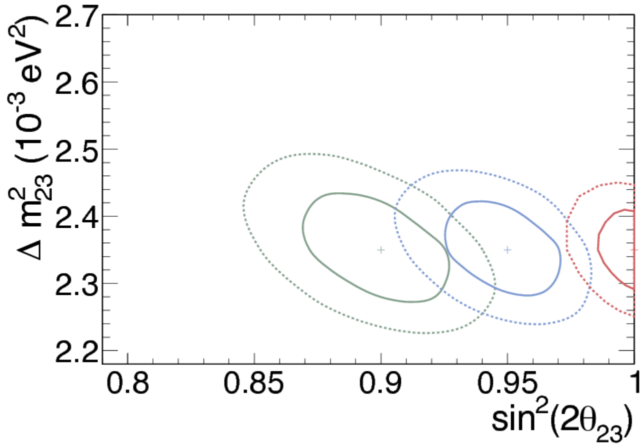
[1] For the NOνA Collaboration.



(a) 90% C.L. Sensitivity to $sin^2(2\theta_{13}) \neq 0$ [2]



(b) 95% C.L. Resolution of the Mass Ordering [2]

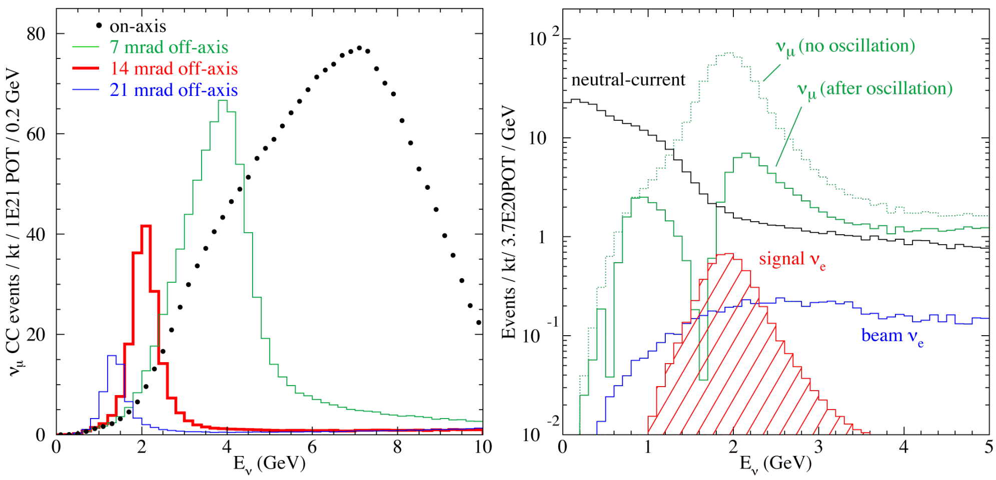


(c) Expected 1σ and 2σ measurements of $sin^2(2\theta_{23})$ [2]

Figure 1: NOνA expected sensitivities for 14-15 kT at L = 810 km with three years running in both ν and $\bar{\nu}$ modes at 700 kW. For Figure 1(a) and 1(b), the blue curves show $\Delta m^2 > 0$ and red curves $\Delta m^2 < 0$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2, $sin^2(2\theta_{23}) = 1$. For Figure 1(b) six years of T2K ν running is assumed. For Figure 1(c) Δm^2_{23} is taken to coincide with recent MINOS measurements and three choices of mixing angle are made consistent with data from Super-Kamiokande.

2.2. *Detectors*

The NOνA detector system consists of a complementary pair of detectors constructed 14 mrad off-axis to the NuMI source. Both detectors will be highly segmented tracking calorimeters built entirely from low Z (~0.15 radiation lengths per layer) PVC, glue, and mineral oil based liquid scintillator with a 65% active volume [2]. The far detector will be a surface based 14 kTon volume located 810 km from NuMI in Ash River, Minnesota. A mound of barite rock over the detector hall (see Fig. 3(a)) will provide an overburden of more than ten radiation lengths. A smaller 222 Ton unit will be built 1.1 km from the source at Fermilab in a 105 meters deep underground cavern. The two detectors will be constructed as similarly as possible to reduce the systematics in the comparison of activity between them.



(a) Neutrino energy distributions [2]

(b) Expected events in off-axis beam [2]

Figure 2: The ν_μ CC energy distribution for various off-axis angles for a medium energy tune in NuMI is shown in Figure 2(a). Figure 2(b) shows raw signal and background rates for the NOvA site, 14 mrad off-axis. The muon neutrino rates are shown with (green dotted) and without (green solid) oscillations applied. The NC rates are shown as a function of the visible energy and pile up at low energies. The blue curve shows the intrinsic beam ν_e component. The red distribution is a ν_e signal at the CHOOZ limit.

(a) Arial view.

(b) Inside detector hall.

Figure 3: Photographs of the NOνA Far Detector Site in Ash River, MN.

3. Near and Far Detector Status

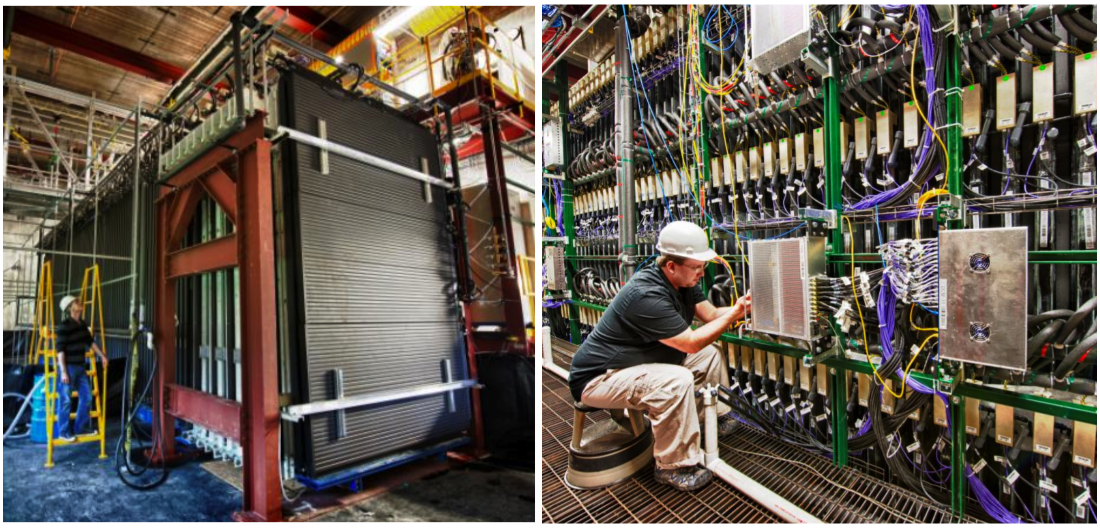
Civil construction of the far detector building (Fig. 3(a)) and hall (Fig. 3(b)) has been primarily completed with beneficial occupancy of the facility being obtained in April 2011. Power and network infrastructure is in place. A 1/8 width full height engineering prototype is currently being built at Argonne National Laboratory and will be erected in the CDF assembly hall this year. Following that, construction of the far detector at Ash River is scheduled to begin in the first quarter of 2012 with a goal to have a detector segment in place before the Fermilab accelerator shutdown. The full detector is on track for completion in the first half of 2014.

Excavation of the underground cavern for the near detector will also begin following the beam shutdown. In the meantime, a near detector surface prototype (NDOS) has been completed and neutrinos from both the NuMI and Booster sources at Fermilab have been observed using the same highly segmented PVC and liquid scintillator detector system that will be deployed in the full scale experiment. This prototype has been taking data since October 2010 and was built to mimic far site construction as closely as possible. Design and initial performance characteristics of this prototype system along with implications for the full NOνAprogram are highlighted in the text below.

3.0.1. PVC Cells

The NOνA detector is built up from a series of extruded TiO_2 loaded PVC cells [2]. Each cell is 3.8 cm by 5.9 cm in cross section with 90% reflectivity for light at 430 nm. Sixteen cells are extruded together as a single part. Two extrusions are joined to together by an end seal and manifold cover to produce a sealed module of 32 cells. In NDOS, the modules are either 4.2 m (vertical orientation) or 2.9 m (horizontal) long while far detector modules are 15.6 m long. These modules are then glued together into alternating planes of horizontal or vertical orientation to creates a self-supporting 32 layer block. Two of these blocks make the smallest operational unit for the NOνA detector. $\sim$360,000 cells makeup the 14 kTon far detector.

For the NDOS, 6 blocks were constructed along with a 1.7 m muon ranger consisting of interleaved steel and module layers (Fig. 4(a)). Building the NDOS allowed the factories and collaboration to fully exercise their quality assurance/quality control (QA/QC) techniques in preparation for full production running for the far detector [3, 4]. This process revealed that $\sim$20% of the manifold cover were cracking upon delivery. These covers have been repaired and a new more robust design with more rigorous control has been adopted for future production. 1200 far detector sized sized extrusion have been produced and accepted to date.



(a) 6 blocks and muon catcher

(b) Close-up of NDOS DAQ

Figure 4: Photographs of the NOνA Near Detector On the Surface.

3.0.2. Liquid Scintillator

Once the PVC block structures are in place, they are filled with with liquid scintillator. The NOνA liquid scintillator is a “home brew” of mineral oil with 5% pseudocumene and wavelength shifters to produce 400-450 nm light. The liquid scintillator makes up 65% of the total detector mass. The scintillator is required to have 80% of the light output of commercial Bicron BC517P at 1 meter [2]. NDOS required $\sim$30,000 gallons of scintillator while the 14 kTon far detector will use over 3 million gallons.

Oil work at NDOS gave us an opportunity to exercise our QA/QC techniques and gain experience in the filing process. Some internal module obstructions were observed during filling; the causes of these has been resolved. NOνA has currently taken possession of around 100,000 gallons of the oil that will be used for the far site.

3.0.3. Fiber

Internal to each cell is a 0.7 mm diameter looped fiber. The fiber shifts the light collected in the scintillator to 490-550 nm. Light is attenuated by a factor of ten over the length of the fiber with redder light (520-550 nm) preferentially surviving [2]. The fiber ends are routed through the manifold covered to an optical connector where they are available for single sided readout. $\sim$113 km of fiber is used in the near detector design with 13,000 km needed for the far detector.

Working with the fiber in advance allowed us to overcome tangling problems related to spooling techniques. We have also gained experience in measuring the fiber performance in realtime as modules are strung. We have receive nearly 50% of all the required NOνA fiber to date.

3.0.4. Avalanche Photodiodes

The light from the fiber ends is incident on an array of 32 Hamamatsu avalanche photodiodes pixels (APD). These devices have 85% quantum efficiency for 520-550 nm light needed to achieve the required energy resolution [2]. The devices are operated with a gain of 100 at 375 V. They are actively cooled to -15 °C to optimize noise characteristics. For NOνA a 20 photoelectron (pe) signal from a minimum ionizing particle at the far end of a far detector sized module is required with a 10-15 pe threshold applied. Based on initial system verification, we expect 38 pe for such a signal, well above the requirement. 496 APD arrays are required for the near detector and about 12,000 are used in the far detector design.

Surface cleanliness and sealing issues have led to many of the NDOS APDs becoming unusably noisy. 274 installed unit have been removed from the detector for cleaning and study. The collaboration is investigating new surface coating and installation techniques which will alleviate these issues prior to far detector construction.

3.0.5. DAQ

The signals from the APDs are processed by front-end electronics (FEBs) which operate in continuous digitization mode and perform a simple baseline subtraction algorithm while sampling each channel every 500 ns [2]. 64 FEBs are fed to a Data Concentrator Module (Fig. 4(b)) which packages and passes the data in 50 μs blocks to a processing farm. The data is then buffered at the farm for several seconds at which point a software trigger may be issued to record all available data in a specified window.

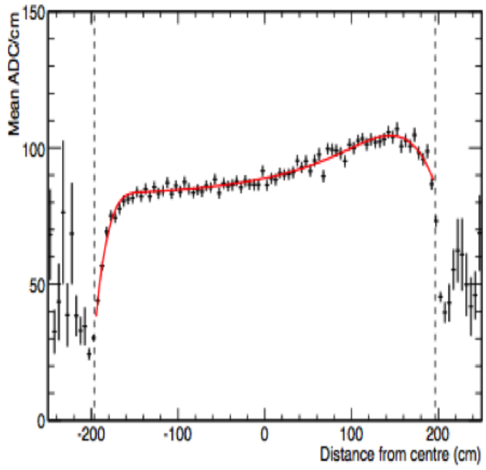
For the near detector, a 500 μs trigger windows was used with three separate trigger sources; the 0.4 Hz NuMI spill signal, the 1.2 Hz Booster beam signal, and a 10 Hz cosmic pulser. The early deployment of the DAQ software has been a boon to NOνA as real throughput capabilities have doubled since initial running [5]. During stress tests of the system stable running was achieved with a 96% duty factor (80 ms trigger windows at 12 Hz).

4. Results from Prototype Near Detector on the Surface (NDOS)

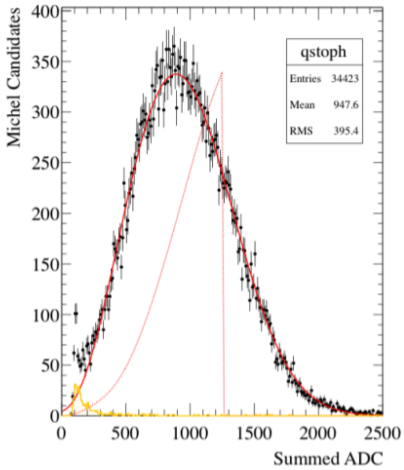
At peak performance, the NDOS ran warm with 75% of its available channels readout. Currently only 45% of the detector is live. Despite this, analysis of the data has begun in earnest. The "gappiness" of our sparse detector has presented challenges in distinguishing muon like events from NC background, but a full suite of monte carlo (masked to behave like our prototype) together with tracking on real data has allowed us to begin to calibrate and reconstruct.

Studies have been performed to understand the energy deposited in the detector and its cell by cell calibrations. Figure 5(a) shows the mean ADC value as a function of the distance from the center of the cell from a cosmic muon sample [6]. One can see the loss in signal at the far end of the volume and a sample curve which could be used to calibrate the detector response. Figure 5(b) shows a sample Michel electron distribution which can be compared again expectation from simulation to provide an electromagnetic energy calibration [7]. Additionally, the observed track length distribution for contained muons reasonably agrees with expectations from monte carlo (Fig 5(c)).

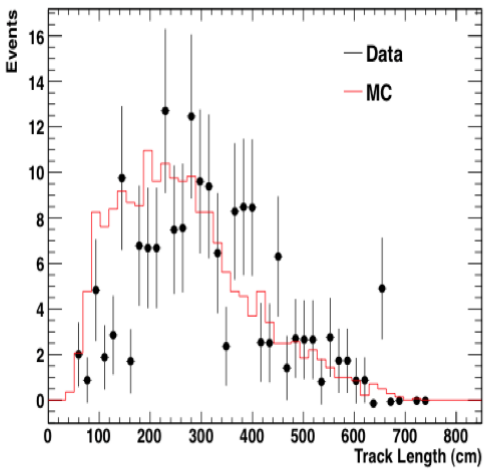
A sample neutrino event for NuMI is shown in Figure 6(a). One can clearly see the long extend muon track in both x and y views as well as the smaller hadronic track. All hits in these tracks occur within a 3 μs window. NDOS has



(a) Attenuation curve from cosmic muons [6].



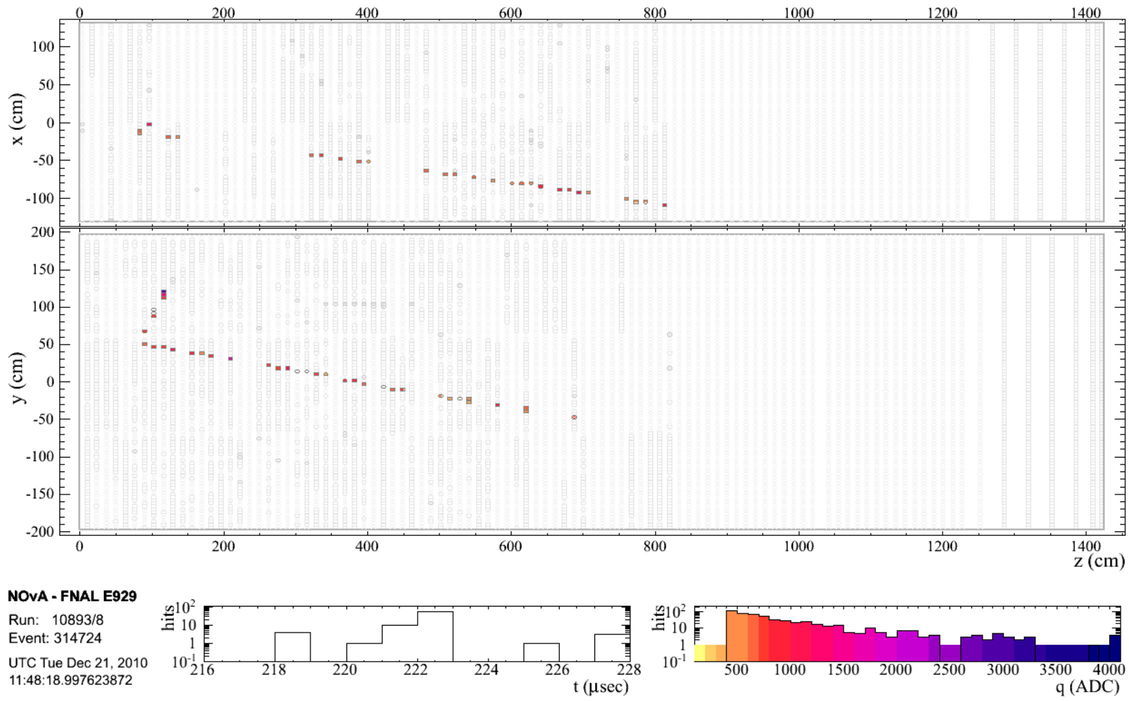
(b) Michel energy spectrum [7].



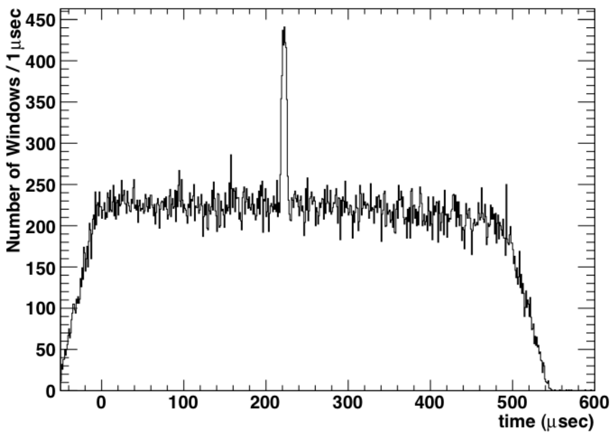
(c) Track length distribution [8]

Figure 5: Preliminary calibration analysis of NDOS.

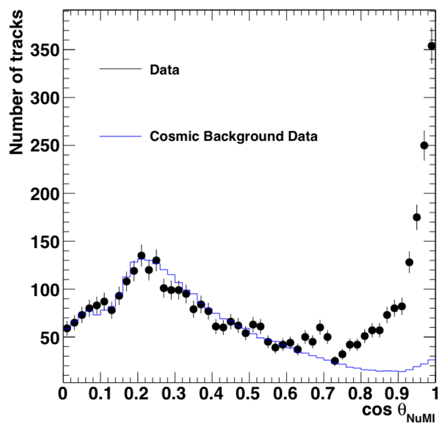
collected 5.6×10^{19} protons-on-target (POT) worth of data in reverse horn current beam and 8.4×10^{18} POT in forward horn mode from NuMI. Analysis of this sample has yielded 1001 and 253 candidate neutrino events with 69 and 39 expected cosmic background events respectively. Figure 6(b) shows a peak of activity in the trigger window at the expected arrival time of the NuMI beam while Figure 6(c) shows an excess of tracks pointing back to the NuMI source over the out-of-time cosmic background [8]. Similar distributions have been see in a Booster neutrino sample of 222 event (with 92 expected background events) from 3×10^{19} POT [9].



(a) Event Display



(b) Timing activity [8].



(c) Angular distribution of tracks [8].

Figure 6: Preliminary analysis of candidate neutrino events from the NuMI source in NDOS.

5. Conclusion

The NOνA NDOS is taking and analyzing data now. This surface prototype has proved invaluable to all aspects of the experimental program, providing critical feedback for design enhancements and operational experience. Recent results from T2K which hint at a large value for θ_{13}, are very encouraging for the long term physics reach of NOνA and open the opportunity to make real contributions in understanding the neutrino. The far detector is on track to begin data taking in 2012, with the detector hall construction nearly complete and expected beam upgrades running on time. The support for NOνA continues to grow with the collaboration now consisting of 110 physicists from 24 institutions in 4 different countries.

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